Spacecraft Modularity for Serviceable Spacecraft

Dino Rossetti, Ph.D.[*]
Conceptual Analytics, LLC, Glen Dale, MD 20769

Beth Keer,[†] John Panek, Ph.D.,[‡] Benjamin Reed,[§] Frank Cepollina[**]
NASA/Goddard Space Flight Center, Greenbelt, Maryland, 20771

and

Robert Ritter[††]
Orbital ATK, Greenbelt, MD 20770

Satellite servicing has been a proven capability of NASA since the first servicing missions in the 1980s with astronauts on the space shuttle. This capability enabled the on-orbit assembly of the International Space Station (ISS) and saved the Hubble Space Telescope (HST) mission following the discovery of the flawed primary mirror. The effectiveness and scope of servicing opportunities, especially using robotic servicers, is a function of how cooperative a spacecraft is. In this paper, modularity will be presented as a critical design aspect for a spacecraft that is cooperative from a servicing perspective. Different features of modularity are discussed using examples from HST and the Multimission Modular Spacecraft (MMS) program from the 1980s and 1990s. The benefits of modularity will be presented including those directly related to servicing and those outside of servicing including reduced costs and increased flexibility. The new Reconfigurable Operational spacecraft for Science and Exploration (ROSE) concept is introduced as an affordable implementation of modularity that provides cost savings and flexibility. Key aspects of the ROSE architecture are discussed such as the module design and the distributed avionics architecture. The ROSE concept builds on the experience from MMS and due to its modularity, would be highly suitable as a future client for on-orbit servicing.

Nomenclature

ACS	=	Attitude control subsystem
C&DH	=	Command and data handling
GSE	=	Ground Support Equipment
GSFC	=	Goddard Space Flight Center
HST	=	Hubble Space Telescope
ISS	=	International Space Station
I&T	=	Integration and Test
MIU	=	Module Interface Unit

[*] Cooperative Servicing Chief Engineer, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771.
[†] Technology Development and Advanced Concepts Program Manager, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771, AIAA Professional Member.
[‡] Cooperative Servicing Chief Architect, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771.
[§] Deputy Project Manager, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771, AIAA Professional Member.
[**] Associate Director, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771, AIAA Professional Member.
[††] ROSE Hardware Manager, Satellite Servicing Capabilities Office, NASA/Goddard Space Flight Center, Code 408, Greenbelt, MD 20771, AIAA Professional Member.

MMS	=	Multimission Modular Spacecraft
NRE	=	Non-recurring engineering
RIU	=	Remote Interface Unit
ROSE	=	Reconfigurable Operational spacecraft for Science and Exploration
SSCO	=	Satellite Servicing Capabilities Office
STIS	=	Space Telescope Imaging Spectrograph
SWARM	=	Self Assembling Wireless Autonomous and Reconfigurable Modules
WFIRST-AFTA	=	Wide-Field InfraRed Survey Telescope – Astrophysics Focused Telescope Assets

I. Introduction

Satellite servicing has been a proven capability of NASA since the first servicing missions in the 1980s with astronauts on the space shuttle. This capability enabled the on-orbit assembly of the International Space Station (ISS) and saved the Hubble Space Telescope (HST) mission following the discovery of the flawed primary mirror. The effectiveness and scope of servicing opportunities, especially using robotic servicers, is a function of how cooperative a spacecraft is. In this paper, modularity will be presented as a critical design aspect for a spacecraft that is cooperative from a servicing perspective. Different features of modularity are discussed using examples from HST and the Multimission Modular Spacecraft (MMS) program from the 1980s and 1990s. The benefits of modularity will be presented including those directly related to servicing and those outside of servicing including reduced costs and increased flexibility. The new Reconfigurable Operational spacecraft for Science and Exploration (ROSE) concept is introduced as an affordable implementation of modularity that provides cost savings and flexibility. Key aspects of the ROSE architecture are discussed such as the module design and the distributed avionics architecture. The ROSE concept builds on the experience from MMS and due to its modularity, would be highly suitable as a future client for on-orbit servicing.

II. Overview of Modularity and Spacecraft Servicing at NASA

NASA has been developing and deploying the technologies required for servicing spacecraft for over 50 years, since the Gemini rendezvous and docking missions. Over time, much more complex missions have been planned and executed. The current state of the art of robotic servicing is repair, life-extension, and mission-enabling activities. This section describes the different types of on-orbit servicing and how modularity of the client spacecraft enables and enhances servicing.

A. Types of On-Orbit Servicing

There are many different goals, clients, and methods for on-orbit servicing. The different types are described here.

1. Goals of on-orbit servicing

On-orbit servicing achieves one or more of three general goals: Life Extension, Repair and Enhancement, and Mission Enabling.

Life Extension: Orbiting assets are often launched with consumable resources such as fuel, oxidizer, or propellant. Over the course of the mission these resources are depleted (e.g. propellant used to maintain an orbit in the presence of slight atmospheric drag or to unload momentum built up in reaction wheels), limiting mission life. On-orbit servicing (e.g. refueling) can be used to replenish the resource so that the mission can continue without the need for relaunching a completely new observatory. The lifetime of the original asset may be greatly extended in this manner.

Repair and Enhancement: Components aboard spacecraft often fail, sometimes right after launch (e.g. a stuck deployment mechanism) and sometimes years later after inadvertent design flaws, ionizing radiation, and orbital debris have taken their toll on electronics, mechanisms, and other spacecraft systems. The Hubble Space Telescope servicing missions demonstrated both of these scenarios. In the first Hubble Space Telescope (HST) servicing mission in 1993, the installation of corrective optics to compensate the flaw in the telescope primary mirror saved the mission. Over the course of time, other failures occurred including the power supply of the Advanced Camera for Surveys, which was repaired with an intricate astronaut procedure during the final servicing mission. Further, replacement of older instruments with state-of-the-art instruments during servicing missions has enhanced the observatory far beyond its original capabilities and allowed it to be on the cutting edge of science over its 25-year lifespan. The modular nature of the scientific instruments aboard HST enabled the enhancement of this flagship

observatory and its science output. The five servicing missions relied on a cooperative client (HST) and the most capable and flexible servicer (astronauts and the space shuttle). Additional mission complexity and execution time are required when the target is not designed for serviceability.

Mission Enabling: The largest and most complex missions require some form of on-orbit assembly. The largest orbiting mission, the International Space Station, has a mass of ~450,000 kg and spans over 100m. It required over 100 flights of the Shuttle, Proton, and others for delivery and assembly of major components and resupply of consumables.

Looking ahead, future scientific missions, such as a life finder telescope, will have components too large for the current generation of launch vehicles. Such an observatory will have a primary mirror in the 20-30m range, required for future objectives such as detection of biosignatures in the atmospheres of exoplanets, but simply too large for the current generation of ~5m diameter launch vehicle fairings. A potential enabling technology for this class of flagship mission is robotic assembly on-orbit, allowing multiple launches of mission hardware to build up to the entire observatory.

B. Type of Client

The types of clients serviced on orbit fall into one of four general categories based on level of cooperation with the servicer and client complexity (normal/small vs. complex/large):

	Cooperative	Non-Cooperative
Facility Class	Examples: HST Types of servicing: Life extension, repair, enhancement. Servicing cost/risk: low Servicing value: High	Examples: JWST Types of servicing: Repair, life extension Servicing cost/risk: high Servicing value: varies (only makes sense to save or extend mission)
Smaller	Examples: MMS, ROSE Types of servicing: Life extension, repair, enhancement. Servicing cost/risk: low Servicing value: High	Examples: Most existent SC Types of servicing: Life extension (refueling), repair Servicing cost/risk: med -high Servicing value: low-high

Figure 1. Types of clients serviced on orbit.

2. Cooperative versus Non-Cooperative

There is a spectrum of serviceability from cooperative to non-cooperative. Cooperative spacecraft incorporate serviceable features into the design from the outset. For HST, for example, these included grappling and docking interfaces for the space shuttle, hand holds and user-friendly interfaces for astronauts, and modular designs that allowed easy replacement of a host of orbit replacement units (ORUs) including components and science instruments. Cooperative spacecraft can easily take advantage of the full range of feasible servicing from life extension through repair and enhancement.

The vast majority of spacecraft, however, are not designed for serviceability. Even for these spacecraft, on-orbit servicing is possible. The Robotic Refueling Mission technology demonstration on the ISS demonstrated technologies that enable an on-orbit refueling capability applicable to non-cooperative spacecraft.[1] However, the range of feasible servicing options for non-cooperative spacecraft is significantly more limited. While some repairs or enhancements may be possible, the complexity of robotic activities would be appreciably higher.

In general, a modular client is a cooperative client. Modules that are replaced easily, with electrical and mechanical interfaces designed for an astronaut or robot to demate and mate, increase the likelihood of successful servicing.

3. Size and Complexity

The size and complexity (and consequently the cost) of a potential client spacecraft define what types of on-orbit servicing are financially feasible. For large, facility-class spacecraft the full spectrum of servicing goals apply. For the largest facility-class project, the ISS, for example, on-orbit servicing and assembly were mission enabling. The ISS required assembly of both pressurized and unpressurized components via astronaut extravehicular activity and robotic assembly, and would not have been viable without these activities. For past and future facility-class science missions, on-orbit servicing may not be mission enabling, but on-orbit repair, mission extension and enhancement are certainly important components in the overall mission strategy. For HST, the replacement of the science instruments, and the accompanying performance enhancements, were part of the mission plan from early on. Likewise, serviceability is planned for the Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA) mission.[2]

Provided a suitable servicing infrastructure exists, smaller spacecraft can also benefit greatly from on-orbit servicing. The Multimission Modular Spacecraft series, for example, included SolarMax, which, as discussed below, was repaired on-orbit by an astronaut team using the space shuttle. The cooperative modular design of MMS helped to enable that mission. However, the economics of servicing small spacecraft limit its applicability and scope when the spacecraft is non-cooperative. Repairs that may be feasible for cooperative spacecraft and cost-effective for large spacecraft, may be too complex (and thus too expensive) for small non-cooperative spacecraft.

4. Examples of Different Types of Clients

The history of shuttle-era repairs contains several examples of smaller and larger, and cooperative and less cooperative clients, and illustrates the relationship between robotic and astronautic servicing capabilities. As mentioned above, in 1984, the SolarMax satellite had lost fine attitude control, greatly limiting the science capability and the space shuttle Challenger was deployed for the first satellite servicing mission for on-orbit repair. During the mission, the satellite was captured and the attitude control system module was replaced. These actions added five years of useful lifetime to the mission. This was only possible because SolarMax was modular and thus cooperative. In another example with a less cooperative client, following launch in 1990, Intelsat VI was stranded in an orbit below its target altitude. In a 1992 servicing mission by space shuttle Endeavor, the satellite had to be hand-captured by three astronauts (see Figure 2). However, the mission was significantly more difficult and risky than planned even though the scope of the servicing task was more limited than for SolarMax.

Aside from the ISS, HST provides the cleanest example of a facility-class, highly cooperative spacecraft. As mentioned above, HST was successfully serviced five times, with astronauts demonstrating ever-more complex repairs. Many of the observatory's components, including the radial and axial science instruments, are modular and designed for easy replacement and servicing. Likewise, many of the spacecraft components were modular and designed for on-orbit replacement, such as the gyroscopes and the batteries. Thus, servicing activities that removed and replaced these elements were generally relatively straightforward. On the other hand, a second class of servicing activities, the in situ repairs of instruments, was more difficult. Repairs of the Space Telescope Imaging Spectrograph (STIS) and Advanced Camera for Surveys required special tools and complex procedures, whereas planned-for instrument replacements did not.

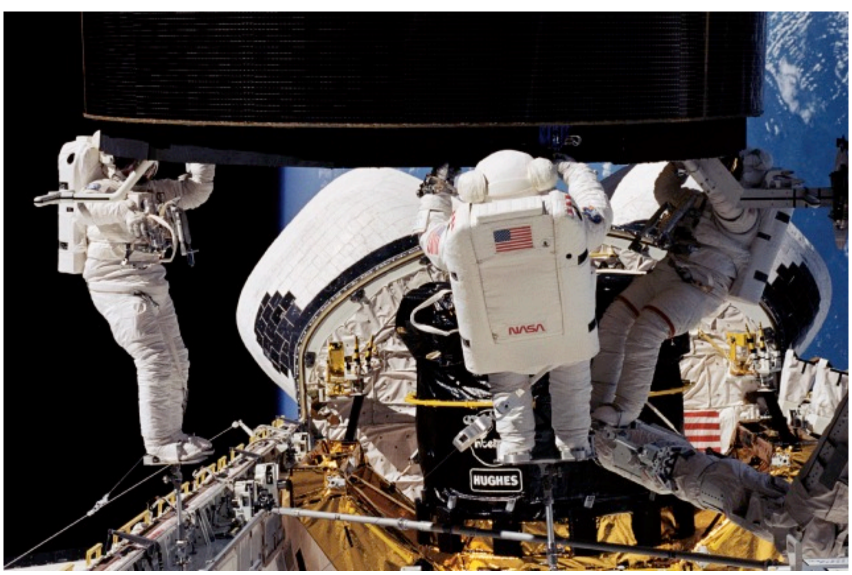

Figure 2. Photo showing three astronauts capturing the Intelsat VI prior to on-orbit servicing.

C. Robotic versus Astronaut

Both robots and astronauts are capable of servicing spacecraft. Their capabilities are different and complementary, and can work together to advance the state of art in satellite servicing as demonstrated by HST and ISS. Historically, only simple tasks were relegated to robotics, leaving the complex to humans. More complex missions requiring adaptability and autonomy tend to need both astronauts and robots. In these hybrid missions, robots can capture spacecraft and support and translate large objects. They can serve to place astronauts in the correct position at a work site, be a second set of eyes, carry tools, etc. That said, as robotic capabilities become sufficient, they will be used alone to minimize cost and unnecessary risk to humans. Having cooperative clients is the key to making servicing missions simpler and thus more robotically friendly.

D. Modularity and Serviceability

Modularity is highly complementary to serviceability (especially robotic). One of the key aspects of modularity, interface standardization, is critical for simplifying servicing tasks so that robots can perform them. As discussed above, robots are best suited to tasks that can be precisely defined and are unlikely to require adaptation. Robust, modular designs fit the bill. A module interface with simple mechanisms can be easily adapted to robotic removal and replacement. Another aspect of modularity, commonality, allows robotic tools and servicing procedures to be reused and thus development costs amortized. This also applies to the development of the interface designs themselves.

III. MMS, HST and ROSE: Approaches to Modularity

For our purposes, modularity in spacecraft has a number of aspects:

- having units with relatively simple interfaces that can be easily removed and replaced,
- grouping of components into these units, and
- the standardization of unit designs, especially interfaces.

Over the years, spacecraft providers have utilized a wide variety of levels and approaches for modularity as summarized in Figure 3. Typical spacecraft are highly integrated with little modularity. Components are individually integrated to the spacecraft, with custom interfaces and locations optimized for elements like harness length and mass properties. One step from this are spacecraft designed with minimal high-level modularity, where the vehicle is built up in two or three large modules, generally to simplify integration and test (I&T) and to allow for parallel schedule paths. This approach can provide significant I&T cost savings[3] but does not necessarily enable on-orbit servicing. In contrast, HST and ISS have significant modularity (including some standard interfaces) that is highly targeted toward servicing as discussed above. MMS and ROSE (described in detail in the sections below) take modularity one step further with standard modules and standard interfaces. In these spacecraft, the majority of spacecraft components are integrated into modules that are easily removed and replaced during I&T and in on-orbit servicing.

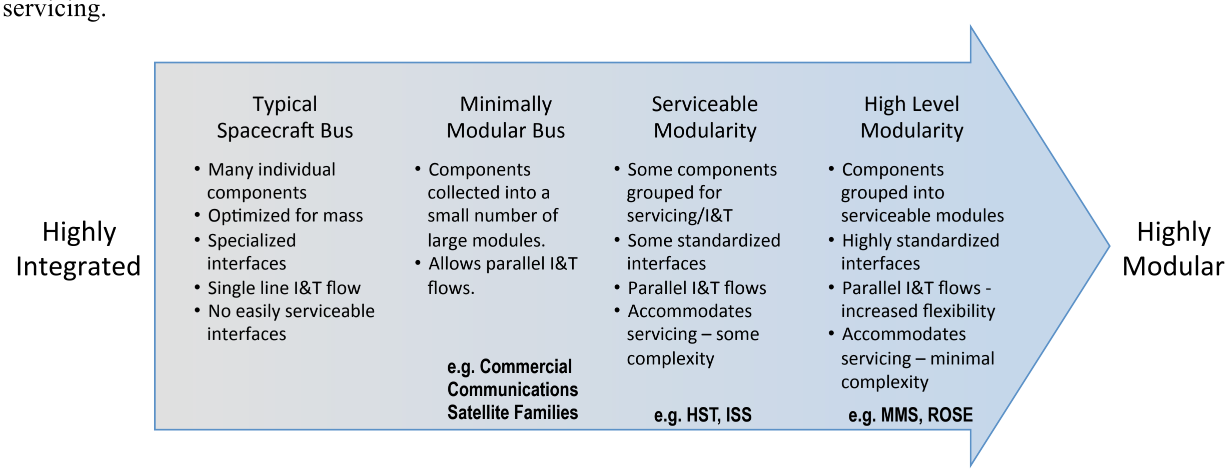

Figure 3. Modularity spectrum.

A. Modularity and Standard Interfaces

By definition, modularity and standard interfaces go hand-in-hand. This is illustrated in the extreme by the concept described by Adomeit, et. al. in which a spacecraft is comprised of a large number of small modules all

sharing the same standard interface.[4] ROSE envisions a less ambitious approach to modularity, but standard interfaces for the spacecraft modules are still critical, including mechanical, electrical and thermal. This standardization allows flexibility, sharing of resources, simplified I&T, and simplified design, and allows for simpler servicing. This will be illustrated in the sections that follow.

B. HST: Modularity at the Component Level

According to David Leckrone, former HST Program Scientist, "Hubble is the most productive science mission, and has had the highest impact, of all NASA science missions in the history of this agency. It's a national icon."[5] Hubble's longevity was accomplished by having component modularity that allowed it to be serviced successfully five times. During each of these servicing missions, failed or degraded components were replaced and the scientific instruments were selectively replaced with state-of-the-art instruments. Almost all the components were designed with interfaces that could be manipulated on orbit. From this perspective, HST is an excellent illustration of the first aspect of modularity listed above (i.e., having units with relatively simple interfaces that can be easily removed and replaced).

However, HST lacked standardization and modular component grouping. So whereas an entire module could be replaced on MMS (and replacing any of the three spacecraft modules would have been a similar task), servicing activities for HST were generally performed at the component level. This meant that tools and procedures had to be developed specifically for each component and each task. Thus, although Hubble servicing was extremely successful, the missions were complex and required a highly orchestrated combination of robotic and astronaut activities.

C. MMS: Modularity at the Subsystem Level

The Multimission Modular Spacecraft (MMS) incorporated component grouping and standardization and was thus a fully modular spacecraft. It used a standard architecture to accommodate the requirements of a wide variety of earth orbiting missions. It was successfully used on five earth science spacecraft.[6] Its modular design allowed major subsystems to be replaced during I&T or on-orbit as demonstrated on SolarMax.

The MMS was designed to provide a basic spacecraft bus to support a wide variety of missions. The basic spacecraft consisted of three subsystem modules, the Power Module, the Command and Data Handling Module and the Attitude Control Module. Each module was attached to the spacecraft structure using a standardized Module Retention System. The Module Retention System provided an on-orbit serviceable interface that not only mechanically attached the module, but also assisted in mating the blind-mate electrical connectors. The MMS also could accept an optional propulsion module.[7]

The three subsystem modules provided the program with a great deal of flexibility. The modules, each competitively bid, could be developed and tested independently from the spacecraft. As technology changed, the internal components of the subsystem could be modified without changing the system architecture.

D. Advanced/Generalized Modularity

A number of teams have proposed advanced, highly modular spacecraft architectures with universal interfaces. These spacecraft would allow for reconfiguration on orbit, thereby requiring common interfaces between the modules. For example, Adomeit et.al. proposed a building block concept.[4] That team concentrated its efforts on developing the primary structural concept and docking interface. Each block would be completely independent, allowing them to be released, detached and rearranged independently in orbit. Rodgers proposed a system called the Self Assembling Wireless Autonomous and Reconfigurable Modules (SWARM).[8] The system was developed in the lab and had four modules (Computer, Attitude Control System, Propulsion, and Mother Ship). Each module shared the following common components: structure, power supply and distribution bus, Field Programmable Gate Array, Metrology Sensors and mechanical interface. The modules were actually designed to automatously unlock, separate, dock and lock. At a higher level, Esper proposed the Modular, Adaptive, Reconfigurable System as a system that would overcome some of the weaknesses he saw with the MMS.[6]

Each of these proposals seeks to utilize concepts that enable highly modular systems within the commercial sphere. In the extreme, for example, interfaces could be intelligent enough to provide plug-and-play capability between modules. Or, spacecraft could be built on the ground or on orbit from a set of configurable semiautonomous "building block" modules that combine to provide all aspects of spacecraft functionality. However, with the limited production volume for spacecraft applications, such approaches may not yet be practical or cost effective.

In the near term, ROSE provides a more limited view of spacecraft modularity, requiring minimal fundamental new technology development, but extending the modularity of MMS to provide flexibility and extensibility.

E. Advantages and Disadvantages of Modularity

The advantages of modularity are well documented.[6,7] The flexibility and standardization inherent with modularity can provide significant savings in system level I&T, both in terms of cost and schedule.[6,7] There are also benefits in the design and production stages from module reuse and minimization of impacts from component-level changes. As discussed below, this is a key piece of the affordability strategy for ROSE. Of course, servicing is another big advantage of modularity. The requirements for a robotic servicer for a remove and replace activity for a cooperative modular interface are far easier than for a less cooperative interface. Modularity carries with it one obvious disadvantage, however: it typically requires additional structural mass as compared with a typical highly integrated spacecraft. For a ROSE sun synchronous mission (up to 700km altitude), with an instrument (payload) capacity of 500 kg, this mass penalty is estimated to be about 42 kg. Cost is also sometimes cited as a disadvantage of modularity, but this is likely to be the case only if just a single spacecraft is considered. For a line of spacecraft, like MMS, and as proposed for ROSE, the added expense for developing the standard interfaces required for modularity is quickly recouped by the cost savings discussed above. For MMS, I&T schedule savings compared with comparable non-MMS spacecraft in the same timeframe, were about 50 to 80 percent.[7] Likewise a study found cost savings of greater than 50 percent.[6]

F. Lessons Learned: MMS and HST

MMS and HST provide excellent examples of different levels of modularity and how it impacts on-orbit servicing, as well as development and I&T on the ground. The tremendous science return from HST, enabled by the five manned servicing missions, is widely acknowledged. During the development of HST and through the course of the servicing missions, NASA developed hardware designs, processes and tools that have applicability beyond HST, including ISS and future missions. Modularity aspects of HST are key carryovers. Commonality of the mechanical interfaces minimized the number of tools and the reliability of the process. Mechanical complexity was imposed on the ground support equipment and servicing infrastructure and tools, not on the spacecraft itself, saving cost. With the component level modularity of HST, however, astronauts were required. Robotic servicing would have been far more challenging and limited in scope.[9] The instrument repairs for the STIS and the Advanced Camera for Surveys, for example, were very complex activities enabled by real-time astronaut operations, many hours of training and preparation and advanced tools. It is difficult to envision how these repairs could have been accomplished robotically.

The advantages of modularity in MMS are discussed throughout this paper. However modularity has been less prevalent in spacecraft designs since MMS. According to Esper,[6] the lack of a dedicated technology development effort for the spacecraft meant that technology improvements were left to individual projects, which had little interest in advancing the MMS spacecraft program in the presence of other less costly options. This, one could argue is a programmatic issue unrelated to MMS's modular architecture, but it does point out that flexibility to adopt new technology is a key to long-term viability for a spacecraft program. Another issue raised by Esper is that the loss of the space shuttle as a servicer for small satellites, meant that there was no servicing infrastructure in-place, negating the servicing advantages of MMS modularity. Following this argument, until a servicing infrastructure is implemented or imminent, the advantages of modularity independent of servicing must be sufficient to merit its adoption.

IV. ROSE

ROSE, being developed by the Satellite Servicing Capabilities Office (SSCO) at the NASA Goddard Space Flight Center, is a low-cost spacecraft concept that seeks to build on the success of MMS using advanced commercial spacecraft technology with a primary focus on long-term affordability. ROSE is being targeted to missions that require a highly capable, medium-size spacecraft but are budget constrained. By filling this niche, SSCO hopes to enhance NASA's ability to demonstrate advanced instrument technology and acquire high-value science at an affordable cost. In parallel, the technologies developed for ROSE will be applicable to future large serviceable observatories such as WFIRST.

A. ROSE Objectives

1. Flexibility – Affordability

The ROSE team believes that modularity and standardization are key features to enable low-cost spacecraft development. The current model is for NASA or commercial spacecraft providers to adapt an existing spacecraft design to a given mission and instrument suite. Such adaptation includes component specification and interface development, and typically ripples across an entire spacecraft, resulting in high non-recurring engineering (NRE)

costs for each mission. ROSE seeks to disrupt this model in a number of ways through its modular architecture. First, because module interfaces are standardized, changes within a module are invisible to the rest of the spacecraft. This means that components can be changed from mission to mission with minimal NRE. This flexibility helps in two ways. First, it allows for spacecraft customization for specific mission requirements. For example, if a mission requires enhanced pointing control, attitude control subsystem (ACS) components can be upgraded without affecting anything outside of the ACS module in which the components (e.g. star trackers) are housed. Second, and perhaps more critically for sustainable cost control, this flexibility allows ROSE to take advantage of component advancements and availability. In the current model, component changes involve trading component cost savings against spacecraft NRE (system level hardware and software design changes, updated analyses and qualification, etc.). Since the cost exercise is generally at the single spacecraft level, the NRE is often higher and the spacecraft is stuck with older components that are higher cost, lower performance or both. In the ROSE model, the additional NRE is limited to a module and thus is potentially much lower. New components can then be cost-effectively adopted, ensuring that the spacecraft bus stays up to date.

In addition, the ROSE model seeks to foster commercial competition within the spacecraft supply chain. Currently, the top tier of the supply chain is limited to a relatively small number of companies that have the expertise to design and build a complete spacecraft. Below this tier are component suppliers. Thus, a large portion of a spacecraft's design and build costs exist at the top of the supply chain where overhead costs are high. ROSE would disrupt this model by enabling competition at the module/subsystem level. Smaller companies with lower cost structures could provide complete modules to the spacecraft integrator. In the ROSE model, the bulk of qualification and acceptance testing occurs at the module level and spacecraft level I&T is minimized. Thus, costs are pushed lower into a more diverse supply chain structure.

Even without changes in the business model, the modularity of ROSE will result in significant cost savings in I&T. Because modules share a standard interface, all of the infrastructure for testing can also be standardized. This includes electrical ground support equipment (GSE), thermal GSE, vibration fixtures, test plans and procedures, systems engineering overhead, etc. In addition, spacecraft level activities will be standardized as well. Integration and de-integration procedures, for example, will be identical across all six modules and thus the learning curve will be significantly accelerated. Since modules will see significant testing at the module level, spacecraft level testing can be reduced (e.g. the number of spacecraft thermal cycles). Finally, there will be increased flexibility for anomalies and sparing. Combined cost and schedule savings in satellite I&T owing to modularity are expected to be significant. For example, as mentioned above, I&T schedules for MMS projects were, on average, more than 50 percent shorter than comparison projects that did not use the MMS spacecraft.[6]

2. Capability – Mission Applicability

The ROSE architecture will be applicable to a wide range of mission scenarios, but for the purpose of early planning, Earth Science applications are being targeted. ROSE is being designed for sun synchronous orbits up to 800 km. To minimize cost, the spacecraft is single sided and targets missions with a NASA risk classification of D.[10] That said, the distributed ROSE architecture would support redundancy, and higher grade parts could be used to accommodate lower risk missions.

B. ROSE Spacecraft Overview

Figure 4 provides an overview of the ROSE spacecraft architecture. The satellite includes three main assemblies/subsystems, the propulsion subsystem, the spacecraft structure and modules, and the instrument platform. All three can be assembled separately in parallel to optimize the overall I&T schedule. The spacecraft includes a single solar array with two deployed panels and a single axis gimbal.

The propulsion system is a bi-prop system designed to take advantage of repurposed components, thus saving significant cost. The tanks, orbit-raising thrusters and other smaller components are reused. New propulsion components include four small thrusters for station keeping and various readily available commercial components. The propulsion system is capable of propelling the spacecraft from transfer orbit of about 300km up to a final sun synchronous orbit at 800km.

The instrument platform is the most mission specific of the three assemblies. ROSE is notionally designed to accommodate from one to four main Earth pointing instruments. Instrument mounting will be quasi-kinematic and the interface will be serviceable allowing for on-orbit instrument replacement.

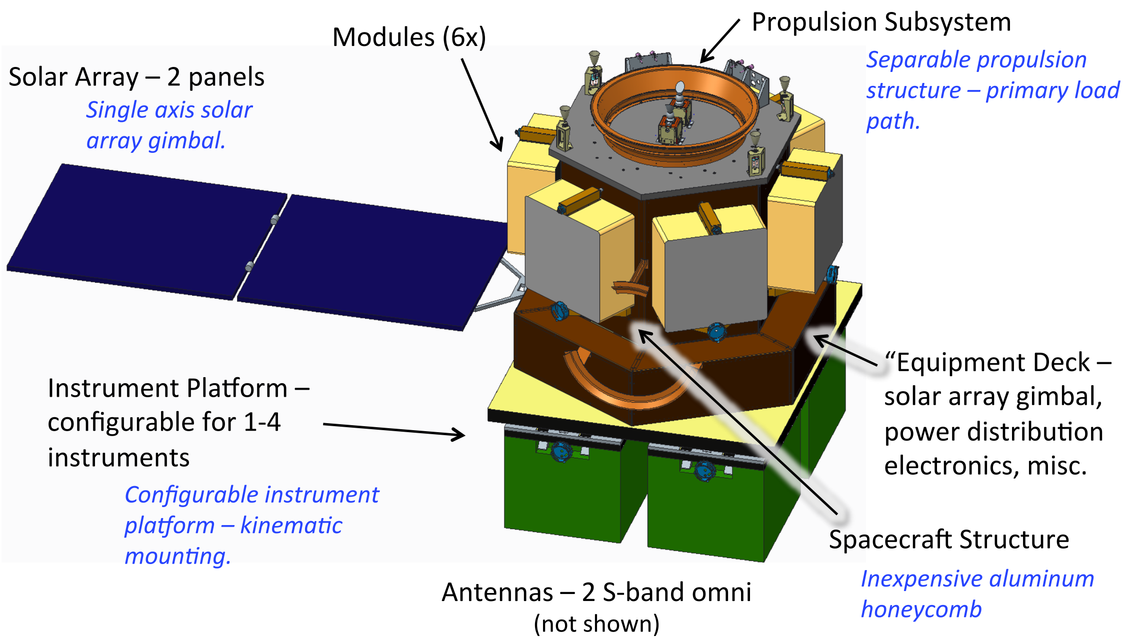

Figure 4. ROSE Spacecraft Overview.

1. Spacecraft Structure

The spacecraft structure, including the modules, is the heart of the vehicle. It fits overtop of the propulsion module as shown in the photograph of the full size mockup at GSFC (Figure 5). The design borrows heavily from the original MMS approach. Above the modules (as shown in Figure 5) is the equipment deck, which includes the solar array gimbal, power distribution electronics and other miscellaneous components that are not intended to be serviceable on-orbit.

Figure 5. Photograph of the ROSE spacecraft mockup at GSFC. *The mockup includes the propulsion system, spacecraft structure, and modules. In the photograph, several modules are left off, revealing the large reuse propulsion tank. The mockup does not yet include an instrument platform.*

Whereas MMS had three relatively large modules, ROSE has six smaller modules. The smaller modules lower the load requirements for the structure, accommodate the serviceable components and provide more flexibility for on-orbit servicing. The structure is being designed to be low cost, utilizing common aluminum honeycomb construction in most places. The modules are designed to be thermally independent and each includes its own radiator, sized to reject the heat that is dissipated within the module. The standard mechanical interface between each module and the spacecraft structure is discussed below.

2. Avionics Overview

Figure 6 provides an overview of the ROSE avionics architecture. Spacecraft components are distributed throughout the modules based on a number of criteria including functionality, size, mass and power. The result includes two ACS modules, a reaction wheel assembly module, a command and data handling (C&DH) module, and a power module. Thus, ROSE subsystems are somewhat distributed as compared to the MMS architecture in which modules were dedicated to complete subsystems (C&DH, power, and ACS).

Within each ROSE module there is a Module Interface Unit (MIU) that provides the standard electrical interface between the module and the rest of the spacecraft. The MIU, discussed in more detail below, provides the backbone to the distributed avionics

approach for ROSE.

The primary communication between modules, and with components outside of modules, is provided by a MIL-STD-1553 serial data bus. While this protocol is relatively slow, it is highly reliable and still in widespread use. Thus, it provides significant flexibility for component selection and thus opportunities for cost savings. Instrument science data, however, which will often require a higher speed interface, is communicated via Spacewire between the instruments and the MIU in the C&DH module.

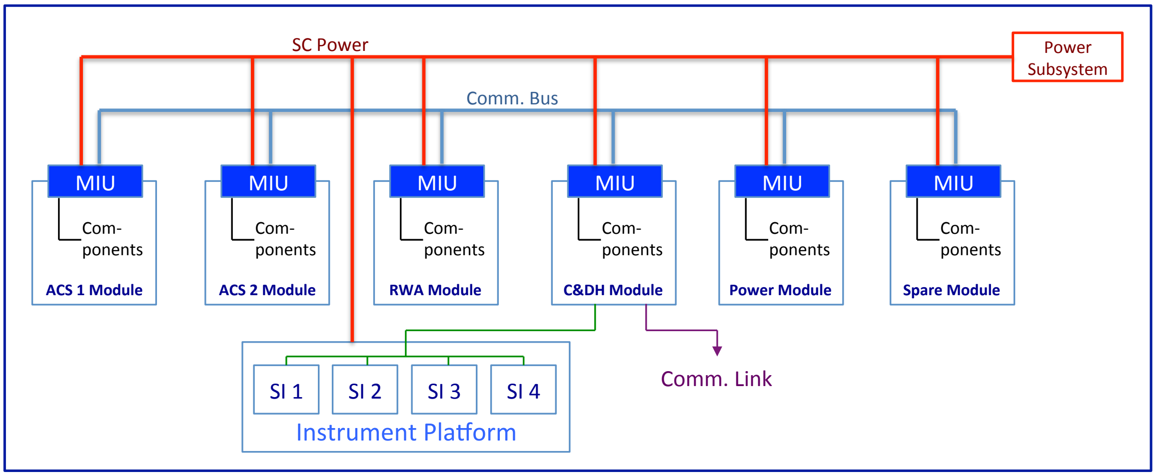

Figure 6. Overview of ROSE avionics architecture.

C. ROSE Modularity

1. Mechanical Interface Description

The mechanism design that provides the mechanical interface between each module and the spacecraft structure is a critical aspect of ROSE modularity. Once again, the design approach borrows heavily on MMS. This mechanical interface has several parallel technical functions (i.e. design drivers):

- It must be highly compatible with ground I&T and on-orbit robotic servicing capabilities, including mating and de-mating of the electrical connectors at the module interface.
- It must be stiff and stable enough to accommodate pointing requirements given that the attitude sensors are housed in a module apart from the instrument platform.
- It must be capable of carrying launch loads.

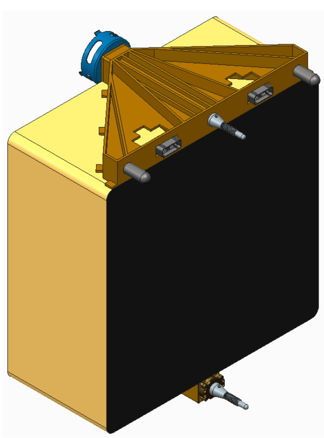

Figure 7. Module mechanical interface notional design.

In addition, it must be inexpensive (and thus simple), small and light. Figure 7 shows the notional design that meets these competing objectives. The actuation is provided by two attachment bolts with coarse threads, which tie the module to the spacecraft structure. These are robotically actuated from the opposite side of the module. The top robotic interface is actuated first during installation and contains means to both hold the module and actuate the bolt. The bottom interface only requires turning of the bolt. Both interfaces are designed to be compatible with the SSCO-developed standard robot interface. In addition to the two bolts, there are three kinematic mounts that provide the positional stiffness and stability and react in-plane launch loads. Finally, large blind-mate electrical connectors provide the physical electrical interface.

2. Modular Interface Unit Description

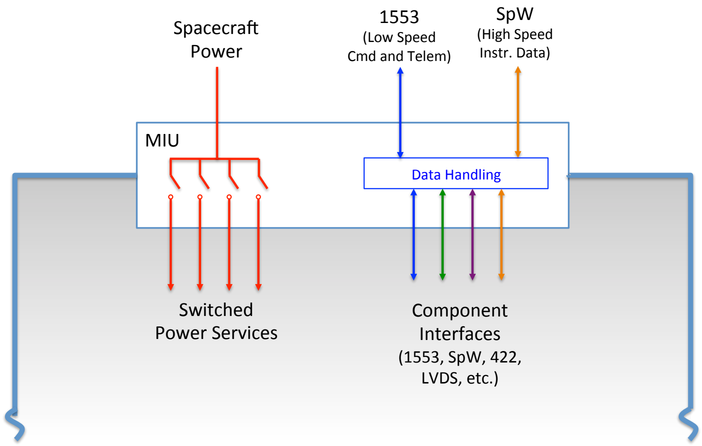

Figure 8. Module Interface Unit interfaces.

An MIU provides the electrical interface between each module and the rest of the spacecraft. The MIUs share a hardware design, but will have different firmware and software based on the functionality of the module. The primary functions of the MIU are to provide a standard electrical interface to the rest of the bus and communication and power interfaces to the components inside the module. The primary external communication interface is the MIL-STD-1553 spacecraft bus. This carries all command and spacecraft telemetry. In addition, the C&DH module will provide a high-speed, point-to-point SpaceWire connection for the instruments. For the components inside the module, however, there is much greater flexibility owing to the variety of options the MIU design provides. To the inside components, the MIU provides 1553, SpaceWire, serial, low voltage differential signal and other interface options. Thus, components may be chosen irrespective of their interface and component changes are possible without affecting the hardware design of the MIU or other spacecraft components.

To enable this flexibility, each MIU has considerable data processing capability. This provides for a distributed avionics approach. For example, whereas attitude estimation is typically performed in the spacecraft computer, in ROSE, it may be performed in the ACS module. Further, the attitude control algorithm that uses that estimate to generate reaction wheel commanding may be implemented in the reaction wheel module. Similarly, functionality and redundancy could be spread throughout the six MIUs.

The implications of this approach for servicing are many. At the least, this architecture allows for straightforward module replacement to supplant failed components. And since changes are isolated to the affected module, the replacement components may be different without impacting the spacecraft. More significant on orbit servicing is also possible. Because new module software can be loaded on orbit, a complete spacecraft reconfiguration is possible. For example, consider the following scenario. A ROSE spacecraft is to be repurposed on orbit through a servicing mission that replaces a low-resolution imaging instrument with a higher resolution version. To accommodate the new instrument, the spacecraft requires better pointing performance and a higher rate communications link. To accomplish this, the instrument, an ACS module and the C&DH module are replaced during the servicing mission. The new ACS module contains higher performance attitude sensors with higher bandwidth and update rates. To take advantage of the new sensors, the control algorithms in the reaction wheel module MIU software are updated during the servicing mission (via commanding from ground operations). Likewise, to take advantage of the higher performance components in the new C&DH module, the software in the other MIUs is updated to provide faster telemetry rates. Thus, as with HST, a servicing mission is able to substantially enhance and refresh the spacecraft's value. However, with ROSE this can be accomplished with relatively straightforward robotic operations.

3. Comparison of ROSE Modularity with MMS

ROSE has adopted many of the design features of MMS. The mechanical module design is heavily influenced by the MMS design including the latches. Similarly, for the avionics, MMS also utilized an interface unit for each module, called the Remote Interface Unit (RIU). However, the MMS RIU lacked the processing capability of the ROSE MIU, and so could not be used to perform functions typically executed in the spacecraft computer. Thus, whereas the MMS C&DH had to be centralized, ROSE is able to adopt a more distributed approach; and with this

comes the flexibility discussed above. Hence, ROSE carries the promise of being able to infuse new technology with a much lower nonrecurring investment.

D. ROSE Technology Development and Future Spacecraft

While the ROSE design limits the need for technology development, some of the critical design features discussed above will be applicable to future cooperative spacecraft. The high performance module latch design of ROSE will be scalable and have applicability for other cooperative modular spacecraft. Likewise, radiation hard electronic parts may be substituted for the commercial parts in the ROSE MIU to produce designs for higher cost, higher reliability spacecraft. More generally, the lessons learned from the architecture studies for ROSE will inform how larger spacecraft approach modularity and servicing.

V. Conclusion

NASA has a long history of on-orbit servicing, from SolarMax in 1984 through ongoing activities on the ISS. In each mission, the servicing activities are matched with the client spacecraft architecture to minimize complexity and risk and thus maximize the value of servicing. This process is most successful in cases where the client spacecraft is designed for servicing and thus cooperative, as demonstrated by the highly successful HST servicing missions. Modularity is perhaps the most critical aspect for a spacecraft architecture to be cooperative. However, modularity provides significant other benefits as well in the areas of flexibility, sustainability and affordability, as was shown with the six MMS spacecraft.

The ROSE spacecraft architecture is designed to utilize the best aspects and lessons learned from MMS, while taking advantage of currently available avionics capabilities to enhance the benefits of modularity. ROSE's modular design and distributed avionics approach allows component changes with a minimum amount of NRE. With this combination of flexibility and affordability, ROSE seeks to become NASA's sustainable affordable platform for scientific instruments. Further, ROSE will be a highly cooperative client spacecraft enabling cost effective servicing opportunities. Finally, designs developed for ROSE will be applicable to other modular cooperative spacecraft in the future.

Acknowledgments

The authors wish to thank Virginia Robinson, the ROSE avionics lead, for her many contributions to, and review of, this paper.

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